DESIGN OF PHASE II UPGRADE AND EXPANSION FOR A WASTEWATER TREATMENT PLANT IN ANHUI UNDER QUASI-IV EFFLUENT STANDARD

YANG, Y.[1,2,3] – SUN, X. H.[2,3] – HUANG, J.[4*]

[1]*School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 230009, China*

[2]*Pollution Control and Resource Utilization in Industrial Parks Joint Laboratory of Anhui Province, Hefei 230041, China*

[3]*Anhui Environmental Science and Technology Group Co., LTD., Hefei 230088, China*

[4]*School of Environmental and Energy Engineering, Anhui Jianzhu University, Hefei 230601, China*

**Corresponding author*
e-mail: 2090253665@qq.com

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Abstract. To address increasing wastewater loads and improve regional water quality, a wastewater treatment plant in Anhui was expanded, increasing its capacity from 10,000 to 40,000 m³/d and upgrading its effluent quality to the quasi-IV standard for surface water. The project augmented the existing oxidation ditch process with two new anaerobic-anoxic-oxic (AAO) biochemical tanks and implemented a novel advanced treatment process combining a high-efficiency sedimentation tank with a sulfur autotrophic denitrification filter. After over a year of stable operation, the effluent indicators are chemical oxygen demand (COD_{Cr}) ≤ 30 mg/L, ammonia nitrogen (NH_3-N) ≤ 1.5 mg/L, total phosphorus (TP) ≤ 0.3 mg/L, and total nitrogen (TN) ≤ 10 mg/L, indicating a significant improvement in effluent quality that consistently meets the quasi-IV class discharge standards. The innovative sulfur autotrophic denitrification technology significantly reduces the need for external carbon sources, lowering operational complexity and costs. The overall plant operational cost is approximately 0.099 USD/m³, with the specific cost for TN removal reduced to just 0.004 USD/m³. This project successfully demonstrates a win-win for both environmental protection and economic efficiency, offering a valuable practical reference for similar upgrade initiatives.

Keywords: *wastewater treatment plant, quasi-IV effluent standard, high-efficiency sedimentation tank, sulfur-based autotrophic denitrification, operational cost*

Introduction

Water resources are a crucial factor in maintaining the balance of ecosystems, human survival, and socio-economic development (Long et al., 2019). However, with economic growth, industrialization, and urbanization, water pollution has become a major environmental issue worldwide, especially in developing countries (Jin et al., 2014). In 2022, 2.2 billion and 3.5 billion people still lacked safely managed drinking water and sanitation, respectively (Mbiankeu Nguea, 2024). Like other developing countries, China is facing increasingly severe water pollution, which is a highly complex problem, characterized by the coexistence of multiple contaminants and pollution sources (Tang et al., 2022). To address this challenge, the Chinese government has invested heavily in wastewater management, strengthening infrastructure and increasing the capacity and number of wastewater treatment plants (Qu et al., 2019; Xia et al., 2024). In this context,

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researching how to gradually expand the scale of wastewater treatment and improve its discharge standards is significantly meaningful for meeting the actual needs of water supply development and mitigating the negative impacts on receiving water (Rathnaweera et al., 2020; Song, 2021). In light of this, we start with practical engineering and explore the technical means to elevate the discharge concentration of major pollutants from standard A of the first-level standard of the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants (GB 18918-2002) to the quasi-IV class standard as per the Environmental Quality Standard for Surface Water (GB 3838-2002), aiming to provide references for the upgrade and expansion of similar wastewater treatment plants and the design of advanced treatment processes. Therefore, this study presents a case study on the upgrade and expansion of a municipal wastewater treatment plant. The primary objective is to analyze its adopted technical process, evaluate the operational effectiveness and economic benefits of elevating the effluent quality to the quasi-IV effluent standard, and summarize the practical experience gained.

Materials and methods

Research background

The wastewater treatment plant of this project is located in the hilly area between the Middle-Lower Yangtze Plain and the Yangtze-Huaihe Region in China. It primarily receives domestic wastewater and industrial wastewater from the surrounding areas, with the Chu River being the receiving water. The initial design capacity was 10,000 m^3/day. However, with the continuous development of economic construction and urban expansion in the region, as well as the increasing number of enterprises settling in the area, the volume of wastewater discharge has been gradually rising. The treatment capacity and process of Phase I can no longer meet the current demands, and its long-term near-capacity operation poses significant risks to achieving standard-compliant discharge.

To meet the increasing volume of wastewater and comply with the latest environmental protection requirements, the existing project is being upgraded and expanded. The design capacity of the Phase II project is 30,000 m^3/d, bringing the total capacity of the wastewater treatment plant to 40,000 m^3/d after the expansion. Following relevant policy documents, to enhance the proportion of high-quality water bodies at the state-controlled section and ensure that the water quality at the state-controlled section of the Chu River meets the standards, the effluent quality of the wastewater treatment plant is being upgraded from the standard A of the first-level standard for urban wastewater treatment plants defined in GB 18918-2002 to the quasi-IV class standard defined in GB 3838-2002 (Li et al., 2018; Liu et al., 2023; Xiao, 2020; Xu et al., 2019).

The Phase I process flow of the wastewater treatment plant is shown in *Figure 1*. The original plant site covers an area of approximately 1.77 hectares. The coarse screen is designed for a maximum flow rate $Qmax = 4333.3$ m^3/h, with a hydraulic variation coefficient $Kz = 1.3$. The fine screen and vortex grit chamber are designed for a maximum flow rate $Qmax = 2287$ m^3/h, with $Kz = 1.37$. The biological treatment unit employs an oxidation ditch process, with a hydraulic retention time (HRT) of 11 h and a solids retention time (SRT) of 13 days. The advanced treatment stage includes a lamellar sedimentation tank and a cloth media filter, with a filtration rate ≤ 6 $m^3/m^2 \cdot h$. Disinfection is carried out using a sodium hypochlorite process, with a dosage of 8 mg/L.

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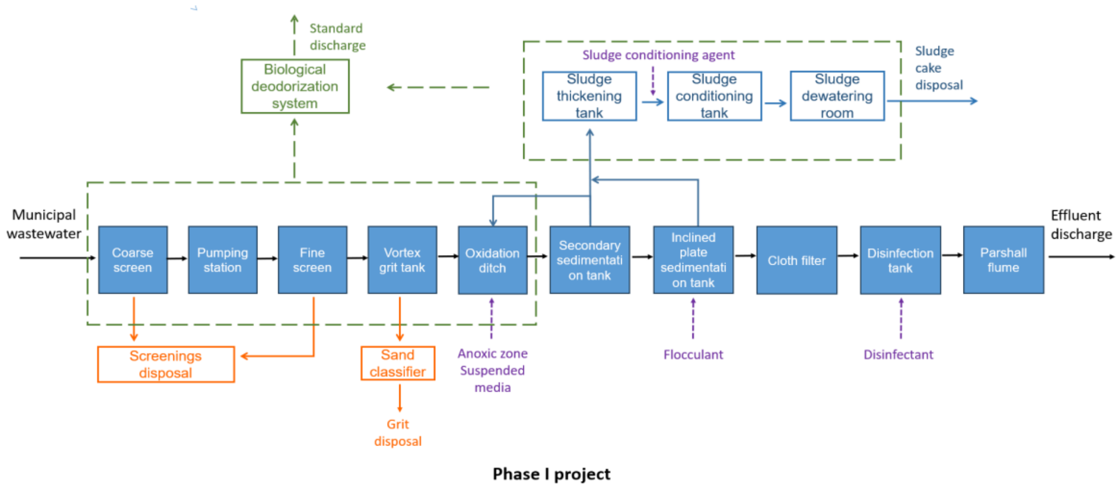

***Figure 1.** Process flow of phase I project*

Sludge treatment involves thickening and conditioning, followed by dewatering using a plate and frame filter press, with the final sludge moisture content being ≤ 60%. The odor control system utilizes biological odor removal technology.

Process flow

Firstly, based on the status of the Phase I project and in combination with the operational data of similar wastewater treatment plants, the influent water quality for the Phase II project was comprehensively predicted. The effluent water quality target is to meet the quasi-IV class standard specified in GB 3838-2002. Accordingly, the influent and effluent water quality for this upgrade and expansion project have been determined, as detailed in *Table 1*.

***Table 1.** Design influent and effluent water quality of main pollutants*

Pollutants	Influent water/(mg·L^{-1})	Effluent water/(mg·L^{-1})	Removal rate (%)
COD_{Cr}	320	30	≥ 90.6
NH_3-N	35	1.5	≥ 95.7
TN	45	10	≥ 77.8
TP	3.5	0.3	≥ 91.4

At present, there are mainly three types of nitrogen and phosphorus removal processes using the activated sludge method in wastewater treatment plants: (1) Anaerobic-anoxic-oxic (AAO) series; (2) Oxidation ditch series; and (3) Sequencing batch reactor (SBR) series. These processes have been widely applied on a large scale in China (Jing et al., 2023; Tan and Wang, 2023; Ye, 2021), and all can ensure that this wastewater treatment plant meets the discharge standards. However, considering that this project is an expansion of an existing plant, detailed analysis and comparison need to be conducted from multiple aspects, including tank matching, civil construction difficulty, power increase, cost, and retrofit examples. Taking both technical and economic factors into account, the AAO process has superior treatment performance,

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stable effluent water quality, advanced and mature technology, high power efficiency, and high operational reliability and flexibility, with stronger nitrogen and phosphorus removal capabilities (Fan et al., 2023). Therefore, it is more suitable for application in this project.

In the advanced treatment unit, this project adopts a combined process of “high-efficiency sedimentation tank + sulfur autotrophic denitrification filter.” The high-efficiency sedimentation tank has the advantages of strong resistance to shock loads, good flocculation effect, fast settling speed of flocs, stable effluent water quality, and small land occupation. The sulfur autotrophic denitrification filter, as a treatment unit integrating biological denitrification and filtration functions, has been widely used in advanced denitrification due to its high denitrification efficiency, no need for external carbon sources, and low sludge production (Bao et al., 2024; Huang et al., 2019). The wastewater treatment process flow for the Phase II upgrade and expansion is shown in *Figure 2*.

Specifically, the wastewater first passes through a coarse screen to remove large floating debris and then is pumped to a fine screen to further remove fine floating debris. The effluent from the fine screen enters a vortex grit tank to remove heavier sand and gravel from the water. After sand removal, the wastewater is distributed into the improved oxidation ditch of Phase I and the AAO biochemical reactor of Phase II, respectively, for anaerobic, anoxic, and aerobic reactions to remove most of the chemical oxygen demand (COD_{Cr}), ammonia nitrogen (NH_3-N), total phosphorus (TP), and total nitrogen (TN). The effluent flows into the secondary sedimentation tank for solid-liquid separation, and the supernatant enters the high-efficiency sedimentation tank. By adding polymeric aluminum chloride (PAC) and polyacrylamide (PAM), SS and TP are removed through coagulation and sedimentation. The effluent then enters the sulfur autotrophic denitrification filter to achieve synergistic denitrification through autotrophic and heterotrophic processes. The effluent from the sulfur autotrophic denitrification filter is disinfected with sodium hypochlorite and then flows through a Parshall flume for discharge up to the standard. To reduce operating costs, the advanced treatment unit of Phase I only serves as a flow-through unit without energy or chemical consumption. Its effluent flows into the Phase II advanced treatment unit, and the final combined effluent is discharged, thereby enhancing the overall stability of the effluent water quality.

Process design

AAO biochemical tank

As shown in *Figure 3,* the biochemical tank adopts a semi-underground AAO combined tank design, with a total of 2 units. Each unit has a designed capacity of 15,000 m^3/d, a design flow rate of 625 m^3/h, and an effective volume of 2847.65 m^3, with an effective water depth of 6.0 m. The mixed liquor suspended solids (MLSS) concentration in the reaction tank is 4000 mg/L, and the sludge loading rate is 0.09 kg BOD_5/(kg MLSS·d). The hydraulic retention times are 2.18 h in the anaerobic zone, 3.36 h in the anoxic zone, and 8.10 h in the aerobic zone, with a total retention time of 13.65 h. In the anaerobic zone, two high-speed submersible mixers are installed, each with a blade diameter of 300 mm and a power rating of 5.5 kW. The anoxic zone is equipped with three low-speed submersible propeller mixers, each with a blade diameter of 2200 mm and a power rating of 5.7 kW. The aerobic zone features 700 fine-

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pore diffusers, four electrically adjustable weirs with an effective width of 2000 mm and an adjustable height of 600 mm (each with a power rating of 0.5 kW), three mixed liquor recirculation pumps, and two submersible wastewater pumps, all with a design flow rate of 620 m^3/h. The recirculation pumps have a head of 1 m and a power rating of 11 kW, while the wastewater pumps have a head of 7 m and a power rating of 22 kW.

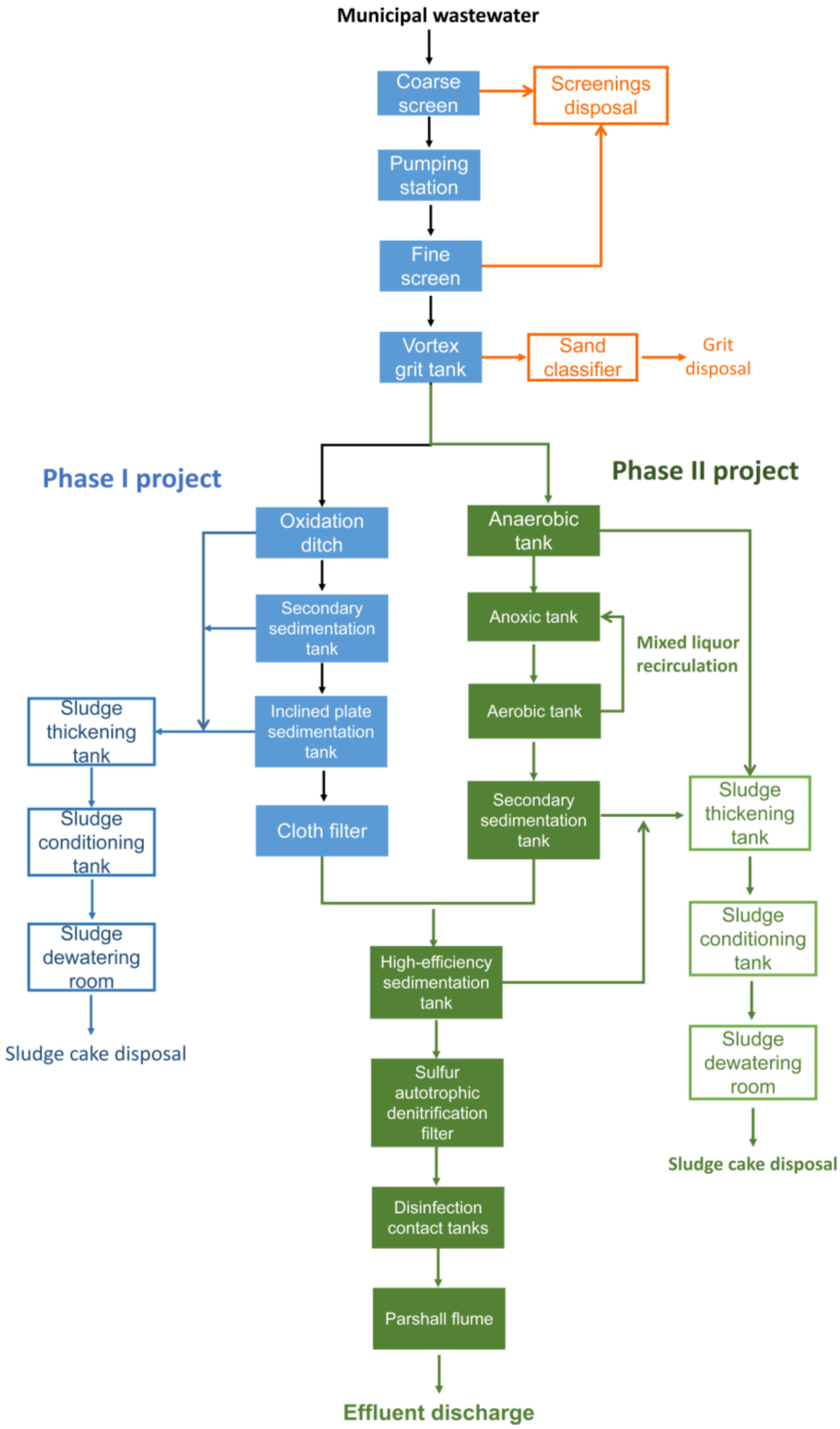

Figure 2. *Process flow of phase II project*

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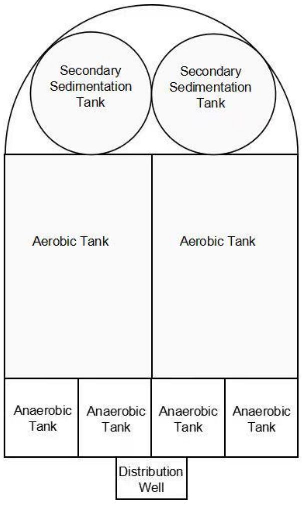

Figure 3. *Phase II expansion of AAO biochemical combined pools*

The secondary sedimentation tank is designed as a peripheral influent and effluent clarifier, with 2 units constructed together with the AAO biochemical tank. Each clarifier has a design flow rate of 937 m^3/h, a surface loading rate of 1.0 $m^3/(m^2 \cdot h)$, a settling time of 6.0 h, and a diameter of 34 m, with a water depth at the edge of the tank of 3.8 m. The dimensions of the sludge discharge well are 10.4 m × 12.4 m. Centrifugal submersible sludge pumps with a non-clogging design are used as both return sludge pumps and excess sludge pumps, with a head of 7 m and power ratings of 22 kW and 3.1 kW, respectively.

High-efficiency sedimentation tank

One high-efficiency sedimentation tank is designed with a plan size of 26.0 m × 18.65 m and a maximum hourly flow rate of 2333 m^3/h. The peak hydraulic retention times are 1.47 min in the coagulation tank and 8.61 min in the reaction tank. The design includes three sludge pumps (two in use and one on standby) with a flow rate of 65 m^3/h, a head of 20 m, and a power rating of 18.5 kW; two mixers with a power rating of 4 kW each; one flocculation mixer with a power rating of 11 kW; and one sludge scraper with a power rating of 1.5 kW.

Sulfur autotrophic denitrification filter

One sulfur autotrophic denitrification filter is designed with four compartments, each with dimensions of 16.70 m × 3.6 m. The maximum hourly flow rate is 1810 m^3/h, with a filtration velocity of 5.20 m/h and a single-tank filtration area of 60 m^2. The filter bed depth is 1.83 m. The backwashing process includes air washing for 3~5 min, combined air-water backwashing for 15 min, and water rinsing for 25 min, with a backwashing frequency of approximately once every 48 h. The filter media consists of a 5 mm sulfur autotrophic inorganic mineral composite material, primarily composed of pyrite, sulfur, limestone, eggshells, and scallop shells. The mineral materials, along with organic matter in the water, serve as electron donors for microorganisms, while nitrate acts as the terminal electron acceptor. Through the autotrophic denitrification process, nitrate is reduced to nitrogen gas.

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Disinfection contact tank

The disinfection contact tank is designed for sodium hypochlorite disinfection, with one unit having a plan size of 42.5 m × 26.5 m, a maximum hourly flow rate of 658.3 m^3/h, an effective water depth of 3.5 m, and a retention time of 6.0 h. Disinfection is carried out using a sodium hypochlorite process, with a dosage of 8 mg/L.

Sludge conditioning tank

One sludge conditioning tank is designed with three compartments, each with a plan size of 6.0 m × 6.0 m and an effective water depth of 4.0 m. Three paddle mixers are installed in the tank.

Integrated building

The integrated building includes a blower room, an electrical distribution room, a chemical dosing and chlorination room, and a sludge dewatering unit. The original blower in Phase I was a Roots blower, and Phase II added five air suspension blowers with a flow rate of 90 m^3/min, a power rating of 115 kW, and an air pressure of 68.6 kPa. The chemical dosing and chlorination room has a plan size of 43.6 m × 10.6 m and includes a PAC dosing room, a PAM dosing room, a chlorination room, and a sodium acetate dosing system. The sludge dewatering unit consists of two sludge thickeners (each with a capacity of 6.0 t DS/d and a sludge moisture content of ≤ 80%) and two plate and frame filter presses (each with a capacity of 6.0 t DS/d and a sludge moisture content of ≤ 60%).

Odor control system

Based on the existing odor control system in Phase I, an additional biological odor control system with a treatment capacity of 5000 m^3/h has been installed. The system includes two fans with a flow rate of 5000 m^3/h, a head of 2400 Pa, and a power rating of 15 kW; a biological filter with a flow rate of 8000 m^3/h; two circulation pumps; one spray well with a flow rate of 15 m^3/h, a head of 20 m, and a power rating of 2.2 kW; and a set of stainless-steel odor collection covers and ducts.

Results

Environmental benefit analysis

The project commenced construction in July 2022 and was completed and entered the commissioning phase in November 2023. Currently, the actual wastewater treatment capacity of the plant averages approximately 28,000 m^3/d. To assess the recent operational performance, the influent and effluent water quality were monitored in November 2024, with the results detailed in *Table 2*. The data in *Table 2* indicate that, in November 2024, the effluent water quality of the wastewater treatment plant met the IV class standards of the environmental quality standards for surface water for all parameters except TN. For a like-for-like comparison, we also compared the pollutant removal rates for November 2021 and November 2024, as detailed in *Table 3*. Additionally, to account for potential seasonality in water quality parameters, we visualized the influent water quality and the corresponding removal rates for the four quarters of 2022 (the pre-upgrade period), as shown in *Table 4*. The results indicate no

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significant variations in either the influent water quality or the removal rates, confirming that our study's findings pass the seasonal sensitivity test.

Table 2. *Actual influent and effluent water quality in November 2024*

Testing parameters		COD_{Cr}/(mg·L^{-1})	NH_3-N/(mg·L^{-1})	TP/(mg·L^{-1})	TN/(mg·L^{-1})
Influent Water	Max	209.00	18.80	7.02	38.96
	Min	107.00	11.51	1.85	15.74
	Mean	158.00	15.16	4.44	27.35
Effluent Water	Max	24.40	0.59	0.26	7.17
	Min	7.80	0.13	0.05	3.21
	Mean	15.90	0.36	0.16	5.19

Table 3. *Average removal efficiency before and after the retrofit*

	Removal rate (%)	
Pollutants/Time	**2024.11**	**2021.11**
COD_{Cr}	90.15	75.86
NH_3-N	79.33	64.98
TN	97.47	76.72
TP	96.27	78.26

Table 4. *Seasonal test of influent quality versus removal efficiency*

	COD_{Cr}		NH_3-N		TP		TN	
Quarter	**Influent**	**Removal rate (%)**	**Influent**	**Removal rate (%)**	**Influent**	**Removal rate (%)**	**Influent**	**Removal rate (%)**
Q1	142.00	73.94	13.55	86.96	3.30	96.41	26.16	58.60
Q2	139.00	77.75	13.25	80.10	2.80	90.64	20.13	56.98
Q3	136.67	74.26	12.35	84.24	3.23	92.78	21.10	57.94
Q4	138.33	73.29	14.30	79.59	3.20	90.78	24.85	57.56

To evaluate the stability of the effluent water quality of the wastewater treatment plant and to continuously track the process operation, the influent and effluent water quality data from January to October 2024 are shown in *Figure 4*. Overall, the daily average values of effluent COD_{Cr}, NH_3-N, and TP were maintained below 30 mg/L, 1.5 mg/L, and 0.3 mg/L, respectively, while the daily average value of effluent TN was stably below 10 mg/L. It can be concluded that, after the upgrade and expansion of the original wastewater treatment plant, the treatment performance has been stably achieving the quasi-IV class discharge standards after one year of operation.

Techno-economic analysis

The total investment in the project was approximately 13.55 million USD, of which the cost of the wastewater treatment project was about 12.77 million USD, and the total land area occupied was approximately 4.48 hectares. After the upgrade and expansion, the actual chemical consumption cost for the plant from January to October 2024 was

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0.023 USD/m³, and the electricity consumption cost was 0.030 USD/m³, with a comprehensive operational cost of about 0.099 USD/m³.

The plant employs a novel sulfur autotrophic denitrification technology, which effectively reduces the costs associated with chemical inputs, the operation of related dosing equipment, and the labor required for equipment maintenance. Compared with the Phase I advanced treatment process, the TN removal cost has been reduced from 0.010 USD/m³ to 0.004 USD/m³.

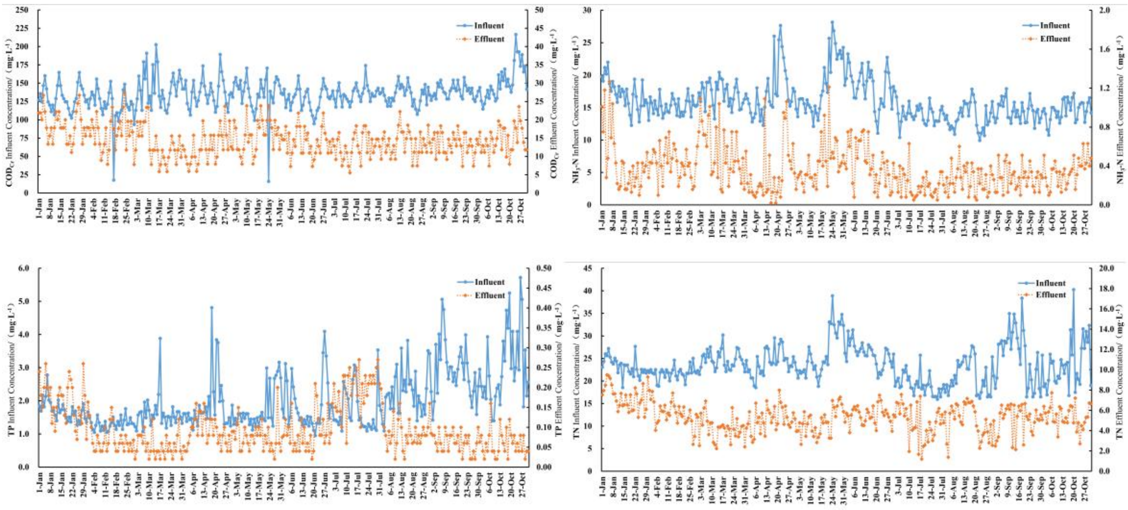

Figure 4. *2024.01~2024.10 index of actual influent and effluent water quality*

Discussion

Compared with conventional approaches, the upgrade project of the wastewater treatment plant in Anhui Province demonstrated superior performance. The effluent indicators—$COD_{Cr} \leq 30$ mg/L, NH_3-N ≤ 1.5 mg/L, TP ≤ 0.3 mg/L and TN ≤ 10 mg/L—indicate a marked improvement in effluent quality that consistently satisfies the quasi-IV effluent standard. A standard anaerobic-anoxic-oxic (AAO) process can rarely meet such stringent limits without costly optimization; the decisive factor here is the innovation introduced at the advanced-treatment stage (Sun, 2021). The unit cost of TN removal in this project is approximately 0.004 USD/m³, which is extremely low compared with conventional heterotrophic denitrification that relies on expensive external carbon sources such as methanol or acetate. These chemicals typically account for a large share of operational expenditure (Fu et al., 2022). Correspondingly, a recent study reported that the operating cost of sulfur autotrophic denitrification is more than 50% lower than that of heterotrophic denitrification (Wang et al., 2021). This project provides a comprehensive real-world validation of the economic and environmental benefits of sulfur autotrophic denitrification, confirming its potential to revolutionize municipal wastewater treatment.

The principal theoretical contribution of this study is the successful integration, at full scale, of the AAO, high-rate sedimentation and sulfur autotrophic denitrification processes. The flowsheet was carefully sequenced: AAO accomplishes bulk pollutant removal, producing a low-C/N effluent that is ideal for the downstream sulfur autotrophic denitrification filters. The high-rate settler protects the biofilters from physical clogging, reduces backwash frequency and ensures the long-term stability and

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health of the slow-growing autotrophic biofilm (Ye et al., 2023). Consequently, sulfur autotrophic denitrification is transformed from a promising but potentially fragile technology (Wang et al., 2020, 2023) into a robust and reliable engineering solution. The configuration offers a replicable and economically attractive template for retrofitting existing wastewater treatment plants, proving that stringent environmental standards can be achieved without prohibitive operating costs.

Notwithstanding these achievements, the study has limitations. Sulfur autotrophic denitrification inevitably generates sulphate as a by-product; elevated sulphate concentrations are regulated in many regions, which may restrict the applicability of the technology in catchments with sensitive receiving waters or stringent local statutes. In addition, the process consumes alkalinity and may depress pH; if not properly managed, this inhibition can compromise microbial activity.

Conclusions

This project based on the original plant's process, has upgraded and expanded the wastewater treatment plant using the "AAO combined biochemical tank + high-efficiency sedimentation tank + sulfur autotrophic denitrification filter + sodium hypochlorite disinfection" process. The summary is as follows:

(1) By introducing the AAO combined biochemical tank, high-efficiency sedimentation tank, and sulfur autotrophic denitrification filter, the concentrations of major pollutants such as COD_{Cr}, NH_3-N, TP, and TN have been reduced from the standard A of the first-level standard of the *Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants* (GB 18918-2002) to the quasi-IV class standard according to the *Environmental Quality Standard for Surface Water* (GB 3838-2002). The treated effluent can be reused as reclaimed water.

(2) After the upgrade, the wastewater treatment plant's comprehensive operating cost is approximately 0.099 USD/m^3. The novel sulfur autotrophic denitrification technology for advanced treatment effectively overcomes the dependence on organic carbon sources for denitrification, achieving energy savings and carbon reduction. The cost of TN removal has been reduced from 0.010 USD/m^3 to 0.004 USD/m^3.

(3) The overall process is characterized by low investment and operating costs, a short renovation period, and highly efficient and stable operation. It not only promotes the improvement of the water environment but also achieves socioeconomic benefits. This project can serve as a reference for similar wastewater treatment plant upgrade and expansion projects.

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